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14. ABSTRACT

Metallic glasses have been designed in order to tune the elastic constants to a condition favorable for increasing the toughness of these glasses. Initial experiments were conducted on a model Ca-based glass to demonstrate the concept, followed by extension to a higher T_g glass. Suction casting in collaboration with AFRL has produced bulk Ca-based glasses. Elastic constants have been measured acoustically and reveal chemically induced changes to the shear- and bulk-modulus, resulting in favorable increases to the poisson's ratio, producing increases to the fracture toughness. Fracture toughness was measured on both notched- and fatigue precracked bend bars and revealed significant increases to the fracture toughness via chemical tuning of the elastic constants. This approach has been extended to higher temperature metallic glasses based on Ni, Ta, and other refractory metal systems. Similar improvements to the damage tolerance have been recorded in these higher T_g metallic glasses. XRD, Hot hardness, elastic constant measurements, and fracture toughness testing followed by SEM analyses of fracture surfaces were used to document the behavior of the model Ca-based glasses as well as the higher T_g glasses.

15. SUBJECT TERMS

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Final Report submitted to AFOSR/Dr. Ali Sayir and Dr. Joan Fuller
PI - Prof. John J Lewandowski, CWRU **Project Started April 1, 2009**
AFOSR-FA95550-09-1-0238

Project Title: Ultra-high Temperature ($T_g \geq 1000^\circ\text{C}$) Amorphous Metals: INTRINSIC and EXTRINSIC Approaches to Discovery and Processing of Tough Hybrids

Executive Summary

Amorphous metals provide unique combinations of functional/structural properties not easily achieved in other systems. However, most amorphous metals examined/produced to date typically have relatively low T_g (e.g. $< 600^\circ\text{C}$), making them unsuitable for very high temperature (e.g. 1000°C) applications due to the extreme softening (i.e. drop in viscosity/hardness) upon approaching T_g , as shown in Figure 1 (1).

Recent work (1,2) on a variety of amorphous metals with moderate T_g (e.g. $T_g < 600^\circ\text{C}$) has revealed a correlation of the INTRINSIC damage tolerance/fracture energy with various elastic constants (e.g. poisson ratio (ν), shear modulus (μ)/bulk modulus (B)) by examining the competition between flow (controlled by shear modulus) and fracture (controlled by bulk modulus), Figure 2. Exceeding a critical value (e.g. $\mu/B > 0.41 - 0.43$) produces embrittlement/low damage tolerance. Changes to the elastic constants can be achieved by alloying, annealing at/near T_g , or a combination of the two.

EXTRINSIC toughening approaches have also been effective in a number of brittle/semi-brittle systems, including ceramics and some other amorphous metal systems (e.g. beta-toughened Zr-based glasses (1)). These approaches rely on EXTRINSIC toughening schemes (e.g. composites, laminates, etc.) as shown in Figure 3 to impede the growth of cracks. Neither the INTRINSIC nor the EXTRINSIC approaches have been previously explored for the amorphous systems of interest above.

Partial support for a post-doctoral researcher, Dr. Joshua Caris, as well as partial support for two PhD students, Lisa Deibler and Chun-Kuo Huang, were provided by this AFOSR grant. Lisa Deibler was also the recipient of an NDSEG Graduate Student Fellowship with AFRL sponsorship. Both Deibler and Huang have recently defended their Ph.D. theses and these are available at CWRU.

Approach and Results

1. Establish collaborations with AFRL (Dr. Dan Miracle + others) on possible glass forming alloys
 - Multiple e-mails beginning in January 2009 and early Spring 2009 regarding possible alloys
 - Lewandowski initial visit to AFRL on 1/28/09 with Dr. Miracle, initial alloy discussions
 - Initial alloys based on Ca-glasses to demonstrate concept of alloy selection for glass formability (AFRL model) and alloy selection for higher toughness (CWRU model), Figure 4.
 - Visit by Lewandowski (PI) and student (Lisa Deibler – NDSEG Fellow) and post-doc (Josh Caris – former NPSC Fellow) to AFRL – 6/30/09
 - Lewandowski seminar to AFRL on 6/30/09, tour of facilities, add'l discussions with AFRL
 - Initial Ca-based glasses processed in bulk quantities (i.e. > 3 mm thickness), Figure 5.
 - Initial Ca-based glasses have poor elastic constants and low toughness in tests at CWRU, Fig. 6
 - New chemistries designed to improve elastic constants (CWRU model) while still showing good glass formability (AFRL model), Figures 4-6.
 - Multiple e-mails regarding possible new chemistries to process at AFRL
 - Second generation Ca-based glasses processed at AFRL and provided to CWRU for testing of amorphicity, hardness, elastic constants, toughness, compression plasticity

- Second-generation Ca-based glasses processed in bulk quantities (i.e. > 3mm thickness)
 - Second generation Ca-based glasses show improved elastic constants and improved intrinsic toughness via ‘tuning’ of elastic constants, Figures 4-7.
 - Initial journal paper being prepared – to be jointly authored at CWRU and AFRL
 - Hot hardness testing at CWRU reveals tremendous hardness/strength drop near T_g, Figure 8.
 - Novel deformation processing used to create EXTRINSICALLY toughened Ca-glass, Figure 9.
 - Hot compression of Ca-glass reduces indentation toughness of Ca-glass, Figure 10.
 - Need to demonstrate concept on high (er) T_g metallic glasses. Figure 11 provides chemistries and initial properties on Ni-based bulk metallic glasses with T_g > 700°C. Fracture surfaces of toughest high T_g glasses exhibits viscous features on fracture surface, Figure 12, consistent with much previous work.
- Program ended prior to expectations despite significant progress demonstrating approach on both a model metallic glass system (i.e. Ca-based glasses) as well as extension of this concept to higher T_g metallic glass systems based on higher melting point elements.

References

1. Lewandowski, J.J., Shazly, M. and Nouri, A.S. (2006). “Intrinsic and Extrinsic Toughness of Bulk Metallic Glasses”, *Scripta Materialia*, Metallic Glasses Viewpoint Set, 54(3), pp. 337-341.
2. Lewandowski, J.J., Wang, W.H., and Greer, A.L. (2005). “Intrinsic Plasticity or Brittleness of Metallic Glasses”, *Philosophical Magazine Letters*, 85(2). pp.77-89.

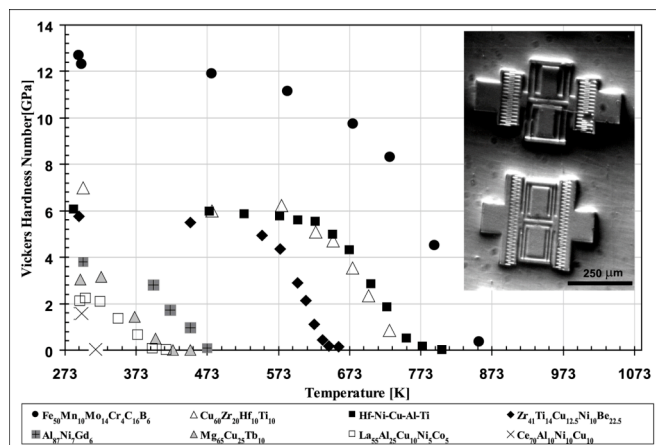


Figure 1. Tremendous softening exhibited by a number of metallic glasses near T_g (1).

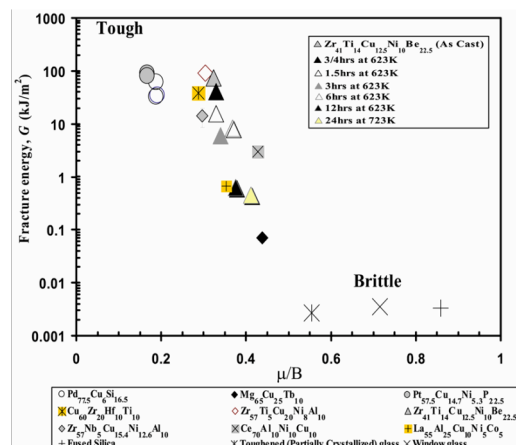


Figure 2. Correlation showing effect of elastic constants on damage tolerance/toughness. Exceeding a critical value of elastic constant ratio produces embrittlement (2).

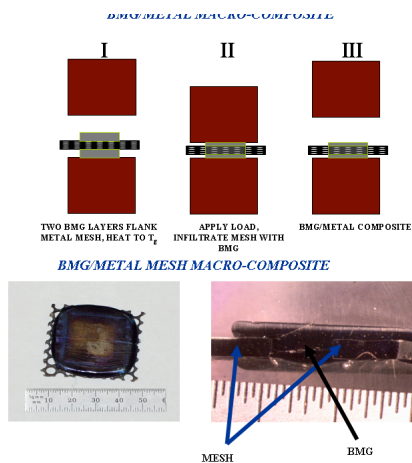


Figure 3. Schematic illustrating process used to produce EXTRINSICALLY toughened Hybrid.

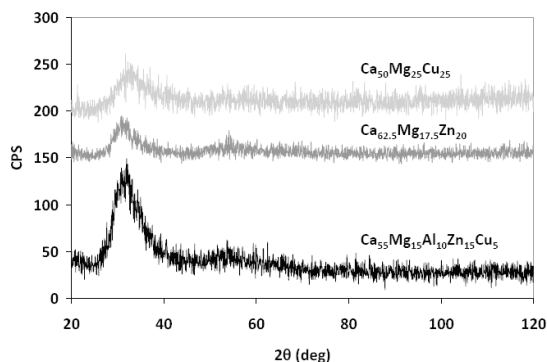


Figure 5. Ca-based amorphous systems. XRD illustrates amorphous nature.

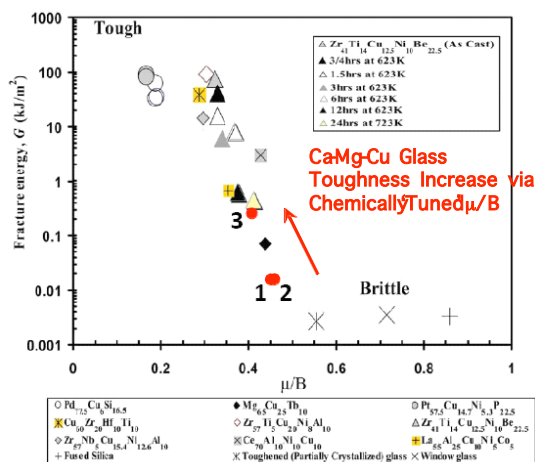


Figure 7. Ca-based amorphous systems with improved toughness via chemical tuning of elastic constants. Other glasses shown for comparison.

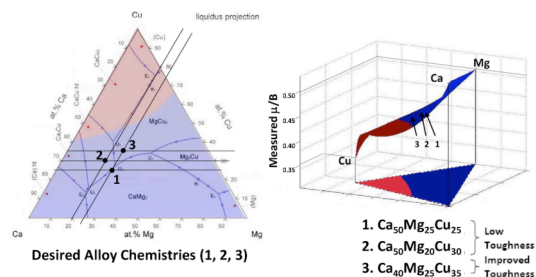


Figure 4. Ca-Mg-Cu Ternary phase diagram showing desired chemistries to 'tune' elastic constants to produce tougher Ca-glass.

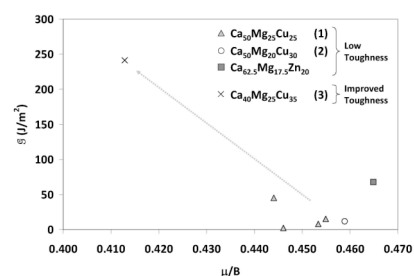


Figure 6. Initial glass chemistries (i.e. 1, 2) have poor toughness. Subsequent chemistry (i.e. 3) exhibits improved toughness.

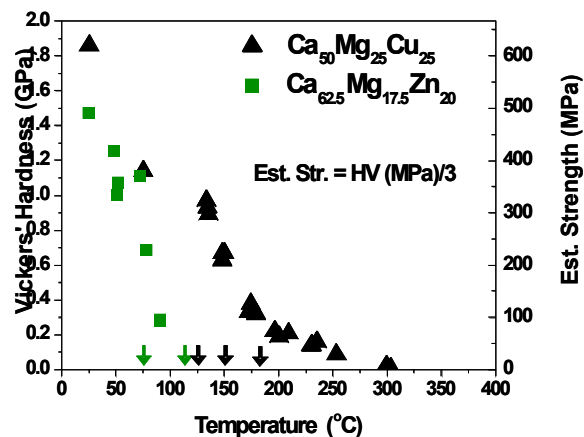


Figure 8. Hot microhardness shows large drop in hardness/strength near T_g , similar to other glasses shown in Figure 1.

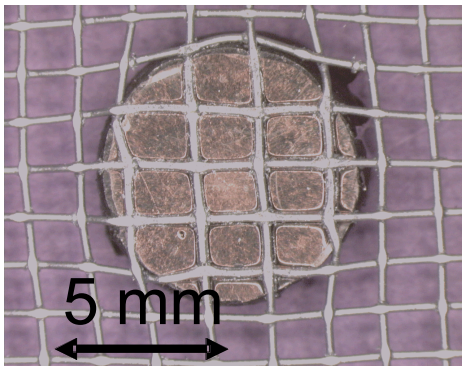


Figure 9. Novel deformation processing of Ca-glass with metallic mesh.

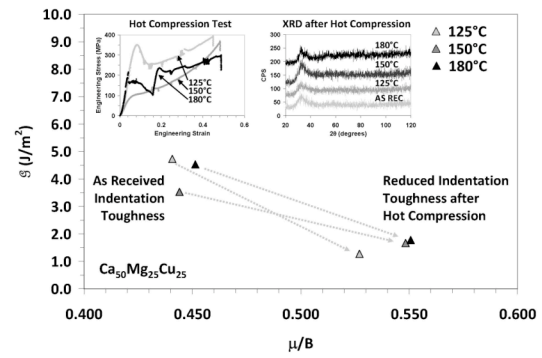


Figure 10. Hot compression of Ca-glass retains amorphicity but reduces indentation toughness.

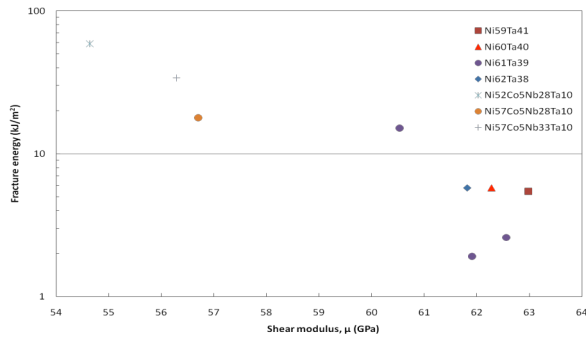


Figure 11. Effects of changes in chemistry designed to 'tune' elastic constants of high Tg glasses. Large increases in toughness possible.

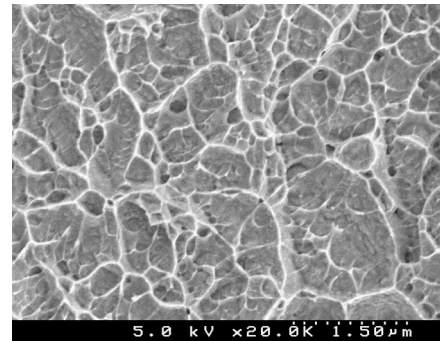


Figure 12. Fracture surface of tough high Tg metallic glass prepared by chemical tuning of elastic constants.